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The planar near-field calibration array (NFCA) was developed by W.J. Trott for use in determining the far-field acoustic radiation from underwater transducers by measurements in the near field. As a projector, the NFCA produces a nearly uniform plane wave over a large volume in its near field and over a large frequency range. As a receiver the NFCA acts like a plane-wave filter for acoustic radiation (or target scattering) originating from within the plane-wave volume. Thus the NFCA can be used to determine the far-field performance of both receiving and projecting transducers. In addition, it can be used to insonify nearby targets with plane waves and determine the resulting scattered far-field pressure. Earlier papers concentrated on the geometrical design of NFCA's and the computation of their relative element responses (or sensitivities) for a specified array configuration, near-field volume, and frequency range. This paper provides analytical expressions for the near-field transmitting voltage and current responses and near-field receiving voltage and current sensitivities of a planar NFCA. The paper also provides information to aid in the NFCA element selection process, especially with regard to shading of the NFCA.

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Near-field transmitting and receiving properties of planar near-field calibration arrays

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The planar near-field calibration array (NFCA) was developed by Trott [W. J. Trott, Underwater Sound Ref. Rep. No. 55 (1961); also J. Acoust. Soc. Am. 36, 1557–1568 (1964)] for use in determining the far-field acoustic radiation from underwater transducers by measurements in the near field. As a projector, the NFCA produces a nearly uniform plane wave over a large volume in its near field and over a large frequency range. As a receiver the NFCA acts like a plane-wave filter for acoustic radiation (or target scattering) originating from within the plane-wave volume. Thus the NFCA can be used to determine the far-field performance of both receiving and projecting transducers. In addition, it can be used to insonify nearby targets with plane waves and determine the resulting scattered far-field pressure. Earlier papers concentrated on the geometrical design of NFCA's and the computation of their relative element responses (or sensitivities) for a specified array configuration, near-field volume, and frequency range. This paper provides analytical expressions for the near-field transmitting voltage and current responses and near-field receiving voltage and current sensitivities of a planar NFCA. The paper also provides information to aid in the NFCA element selection process, especially with regard to shading of the NFCA.

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INTRODUCTION

Trott[1-3] developed the planar near-field calibration array (NFCA) for use in determining the far-field acoustic radiation from underwater transducers by measurements in the near field.

The planar NFCA is a large array of small reciprocal transducers (elements) that are arranged in a grid that is usually square but can be circular, hexagonal, or any other pattern that distributes the elements somewhat uniformly over the array. The relative acoustic outputs of the elements are selected so that the array, when driven as a projector, produces a nearly uniform plane wave over a volume V in its near field and over a wide frequency range Ω. As seen in Fig. 1, the direction of the plane wave $\hat{e}$ is usually normal to the NFCA. A transducer to be calibrated is placed in the plane-wave volume, and the NFCA is used as a receiver. The response of the NFCA is then proportional to the far-field pressure distribution $f(\hat{e})$ of the transducer in the direction opposite to the plane wave. The far-field pressure distribution is defined as the acoustic pressure produced by the transducer at the far-field distance R divided by the factor e^{-ikR}/R to remove the distance dependence. Here the wave number k is equal to $2\pi/\lambda$, where λ is the wavelength and R is the far-field distance as measured from the center of the NFCA.

The NFCA concept is based on the NFCA reciprocity principle. A previous paper[8] gives the derivation of this principle. In addition a numerical procedure is given there for calculating a least-squares solution for the relative shading of the NFCA elements for a prescribed array configuration, plane-wave direction $\hat{e}$, near-field volume V, and frequency range Ω. This procedure has been used to design steered planar[4], cylindrical,[5,6] and spherical[7] NFCA's. Recently there has been a resurgence of interest in planar NFCA's, both for projecting and receiving applications. Earlier pa-

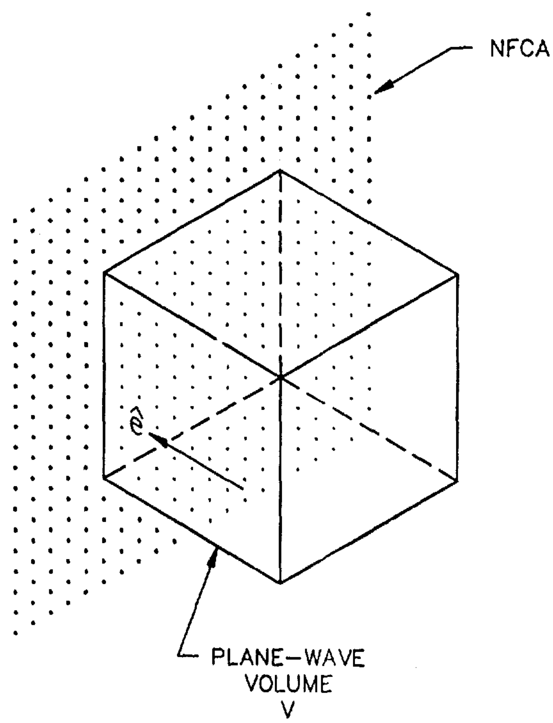

FIG. 1. Planar near-field calibration array and associated plane-wave volume.

pers concentrated on the geometrical design of NFCA's and the determination of their relative element shading. The purpose of this paper is to provide for the first time expressions for the near-field transmitting response and receiving sensitivity of a planar near-field calibration array (NFCA). The near-field transmitting voltage (current) response of the NFCA is defined to be the ratio of the near-field plane-wave pressure produced by a projecting NFCA to the NFCA input voltage (current). The phase of the plane-wave pressure is taken to be that produced at a reference point located a distance 1 m from the center of the NFCA in the direction $\hat{e}$ of the plane wave. If the reference point does not lie within the plane-wave volume V, then the phase of the near-field pressure is extrapolated from the plane-wave volume to the reference position. It is convenient to define a reference distance D equal to 1 m. The near-field receiving voltage (current) sensitivity of the NFCA to a transducer located in the plane-wave volume V is defined to be the ratio of the voltage (current) generated in the NFCA to the far-field pressure distribution $f(\hat{e})$ of the transducer divided by the reference distance D.

Element shading for the planar NFCA is described in Sec. I. Expressions for the near-field transmitting responses of the planar NFCA are obtained in Sec. II. Section III provides corresponding expressions for the NFCA near-field receiving sensitivity. Modifications to the expressions for the case where complex shading coefficients are used are discussed in Sec. IV. The paper concludes with the summary in Sec. V.

I. ELEMENT SHADING

Consider the case of a rectangular planar NFCA, as shown in Fig. 1, consisting of L identical, equispaced, straight-line arrays each containing Q equispaced small-piezoceramic transducer elements whose fundamental resonance frequency is well above the operational range of the NFCA. Shading coefficients can be obtained for this NFCA by a two-step least-squares process. First shading coefficients α_q, $q = 1, 2, \ldots, Q$, are computed for the elements in a single line such that the line produces a nearly uniform cylindrical wave over the desired plane-wave volume V and over the operational frequency range Ω of the NFCA. Then additional shading coefficients β_l, $l = 1, 2, \ldots, L$, one coefficient for each line in the NFCA, are computed such that the entire array produces a nearly uniform plane wave throughout V and Ω. For this latter computation one uses the plane-wave requirement given in Refs. 3 and 4:

$$\sum_{l=1}^{L} \beta_l \sum_{q=1}^{Q} \alpha_q \exp(ik\mathbf{r}_{lq}\cdot\hat{e}) \frac{\exp(ik|\mathbf{r}_{lq}-\mathbf{r}|)}{\lambda|\mathbf{r}_{lq}-\mathbf{r}|} = i\exp(ik\mathbf{r}\cdot\hat{e}), \tag{1}$$

where $\mathbf{r}_{lq}$ is the location of the qth element in the lth line, $\mathbf{r}$ is a point in the near-field plane-wave volume, and $\hat{e}$ is a unit vector in the direction opposite to the desired plane wave produced by the NFCA. The origin of coordinates is taken to be the center of the NFCA. Figure 2 shows the geometry of the problem. [Note that α_q was inadvertently omitted from Eq. (6) in Ref. 4.]

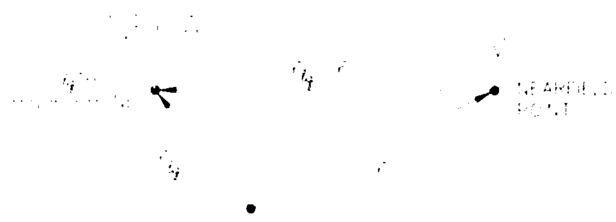

FIG. 2. Geometry of the problem.

Equation (1) cannot be satisfied exactly for any finite volume V. However, with proper design of the NFCA, shading coefficients α and β can be obtained that approximately satisfy Eq. (1) to within a few percent in amplitude and a few degrees in phase throughout a large near-field volume V and over a large frequency range Ω. This capability is the reason for the success of the NFCA. By comparison, the near-field pressure distribution in front of a similar size uniformly vibrating piston varies from near zero to twice the nominal plane-wave value, the variation being especially strong near the piston axis.

The total shading for the qth element in the lth line is $\beta_l\alpha_q$ times the plane-wave phase factor $\exp(ik\mathbf{r}_{lq}\cdot\hat{e})$. For the present discussion $\hat{e}$ is assumed to be the outward normal to the plane of the array. In this case $\hat{e}$ is normal to $\mathbf{r}_{lq}$ so that the plane-wave phase term is equal to unity for all l and q. It is convenient to normalize α_q by the spacing Δx between elements to obtain

$$\alpha_q = \alpha_q' \Delta x = \alpha_q'[d/(Q-1)], \tag{2}$$

where d is the length of each line in the NFCA. It is also convenient to normalize the line shading β_l by the spacing Δy between lines in the NFCA to obtain

$$\beta_l = \beta_l' \Delta y. \tag{3}$$

The quantity $A = \Delta x\, \Delta y$ is the effective area of a transducer element in the NFCA. [If $\hat{e}$ were chosen oblique to the plane of the NFCA at an angle γ given by $\cos^{-1}(\hat{e}\cdot\hat{e}_z)$, then the effective area A would be given by $\Delta x\, \Delta y \cos\gamma$. See Ref. 4 for a discussion of the steered planar near-field calibration array.]

The shading coefficients α_q and thus the normalized coefficients α_q' are usually chosen to be real quantities, representing amplitude shading only. Values for α_q' range from 0.1 or so for elements near both ends of the line to near unity for one or more of the center elements. The least-squares process for computing α_q tends to produce values for α_q' for one or more of the elements near the center of the line that differ less than 1% from unity. Treating these coefficients as equal to unity will not degrade the performance of the NFCA. Alternatively, one can constrain the least-squares algorithm to produce unity shading coefficients for the center elements, again without significant degradation of the NFCA.

The choice of real coefficients allows the shading of the elements in each line (called the internal line shading) to be implemented passively. This is done by connecting the elements in each line in parallel electrically and using series

shading capacitors to adjust the relative effective transmitting voltage response (TVR) of each of the elements so that it is proportional to α'_q. That is,

$$(S_{T,q})_{sh} = S_{T,q}[C_{sq}/(C_q + C_{sq})] = \alpha'_q S_{T,ref}, \qquad (4)$$

where $S_{T,q}$ is the unshaded transmitting voltage response, C_q is the capacitance, and C_{sq} is the required value of the series shading capacitor for the qth element. Here $S_{T,ref}$ is a reference TVR value, chosen to be the maximum TVR value among the unshaded elements. The element with the maximum unshaded TVR should be selected for the maximum, i.e., unity value of α'_q. Then the other elements should be selected so that $S_{T,q}$ is greater than or equal to $\alpha'_q S_{T,ref}$. Otherwise, use of Eq. (4) will lead to the physically impossible requirement for a negative value of C_{sq}.

An adjustment of the TVR's for reciprocal transducer elements is equivalent to an adjustment of the receiving current sensitivities. This in turn is equivalent to an adjustment of the quotients $M_q/Z_{e,q}$ of the receiving voltage sensitivities M_q and the element electrical impedances $Z_{e,q}$. For piezoceramic elements at frequencies well below their fundamental resonance, the electrical impedance is essentially that of a capacitor, i.e., $Z_{e,q} = 1/i\omega C'_q$, where ω is the angular frequency ($= ck$, with c being the sound speed in water) and where C'_q is the capacitance of the series combination of the element and its shading capacitor. Thus one essentially adjusts the $M_q C'_q$ products of the elements to be proportional to the coefficients α'_q. That is,

$$M_q C'_q = \alpha'_q (MC)_{ref}, \qquad (5)$$

where $(MC)_{ref}$ is equal to the product of the receiving voltage sensitivity and the capacitance for the element(s) with α'_q equal to unity.

A large number of hydrophone elements are usually required for a planar NFCA. Prior to constructing the NFCA, it is convenient to obtain several times this number of elements, divided into three or four slightly different geometrical configurations or possibly even different piezoceramic compositions designed to have MC product values that are distributed over the range from about 0.4 $(MC)_{ref}$ to $(MC)_{ref}$. For example, the wall thickness of a capped PZT cylinder can be varied to obtain most of this range. The normal distribution of the MC product values of the delivered elements about the nominal values that were ordered results in a full representation of MC product values from about 0.35 $(MC)_{ref}$ to 1.05 $(MC)_{ref}$. Selection of appropriate elements with natural MC product values equal to $\alpha'_q (MC)_{ref}$ can usually be made for all values of α'_q from 0.35 to 1.05 resulting in a need for shading capacitors for only those few elements on each end of the line that possess α'_q values less than about 0.35.

For unsteered planar NFCA's, the coefficients β' are also usually chosen to be real, ranging from 0.1 or so for the outside lines on both sides to near unity for the center lines. As with the internal shading coefficients α'_q, the least-squares process tends to produce values for β'_l for one or more of the lines near the center of the NFCA that differ less than 1% from unity. As previously, treating these coefficients as equal to unity will not degrade the performance of the NFCA. The choice of real coefficients β' allows the relative shading of the lines (called the external line shading) to be implemented passively. This is done by connecting all of the lines in parallel and using a series shading capacitor for each line to adjust the relative TVR (or equivalently the MC product) of each line to be proportional to β'_l. Here M is the broadside far-field sensitivity and C is the total capacitance of the line. The MC value for each line is given by

$$MC = \sum_{q=1}^{Q} M_q C'_q$$

or $\qquad (6)$

$$MC = (MC)_{ref} \sum \alpha'_q.$$

Thus if $(MC)_{ref}$ is chosen to be the same for all of the lines, the MC values of each line are also equal. In this case the series capacitance required for the lth line C_{sl} is calculated using

$$C_{sl}/(C_l + C_{sl}) = \beta'_l, \qquad (7)$$

where C_l in the total capacitance of the line without the series capacitor and where β'_l is assumed to be less than unity. For $\beta'_l = 1$, no shading capacitor is required.

When the selection of available hydrophone elements is relatively limited, different $(MC)_{ref}$ values can be chosen for one or more of the lines in order to allow elements to be selected for those lines with only a few elements requiring shading capacitors. When the $(MC)_{ref}$ values are not the same for all of the lines, the lines should be shaded externally using series capacitors calculated using

$$C_{sl}/(C_l + C_{sl}) = [(MC)_{max}/(MC)_{ref,l}]\beta'_l, \qquad (8)$$

where $(MC)_{max}$ is the maximum value of $(MC)_{ref,l}$. We note that the $(MC)_{ref,l}$ values should be chosen carefully to prevent the right-hand side of Eq. (8) from becoming greater than unity, thereby requiring nonphysical negative values for C_{sl}. Lines with β'_l equal to unity must possess $(MC)_{ref,l}$ values equal to $(MC)_{max}$. No shading capacitor is required for these lines. We now define the reference quantity $(MC)_{ref}$ to be $(MC)_{max}$ in order to simplify the equations derived below.

When the entire NFCA has been passively shaded by the use of appropriate capacitors, it can be driven through a single twisted pair or coaxial input. If the hydrophone elements are reciprocal transducers, the NFCA is also reciprocal and can be used in the receiving mode as a plane-wave filter for sound radiated or scattered from the plane-wave volume V.

The coefficients β_l and, consequently, β' can be chosen to be complex, containing both amplitude and phase shading. The extra L degrees of freedom in the shading allows for significantly improved NFCA performance (i.e., better plane-wave uniformity throughout V and Ω) but at the expense of complicating the shading and/or drive requirements. One can implement complex shading passively if shading components can be developed for each line (or symmetrical pair of lines) that provide a constant phase angle over the operational frequency range Ω. (A possibility here is the use of orthogonally wound transformers). Alterna-

tively one can drive each of the lines independently with separate but properly phased amplifiers.

II. NEAR-FIELD TRANSMITTING RESPONSE

For the case of passive capacitance shading, Eq. (1) can be rewritten for $\hat{e}$ normal to $\mathbf{r}_{lq}$ to obtain

$$\Delta x\,\Delta y \sum_{l=1}^{L} \beta'_l \sum_{q=1}^{Q} \alpha'_q S_{V,\mathrm{ref}} \frac{D\exp(-ik|\mathbf{r}_{lq}-\mathbf{r}|)}{|\mathbf{r}_{lq}-\mathbf{r}|\exp(-ikD)} = -i\lambda D S_{V,\mathrm{ref}} \exp(ikD)\exp(ik\mathbf{r}\cdot\hat{e}) \tag{9}$$

or

$$\sum_{l=1}^{L} \sum_{q=1}^{Q} (S_{V,lq})_{\mathrm{eff}} \frac{D\exp(-ik|\mathbf{r}_{lq}-\mathbf{r}|)}{|\mathbf{r}_{lq}-\mathbf{r}|\exp(-ikD)} = -i\frac{\lambda D S_{V,\mathrm{ref}}}{A}\exp(ikD)\exp(ik\mathbf{r}\cdot\hat{e}), \tag{10}$$

where $(S_{V,lq})_{\mathrm{eff}}$ is the effective transmitting voltage response of the (l,q)th element in the NFCA, and D is again the reference distance of 1 m as used in the definition of S. The left-hand side of Eq. (10) is the total acoustic pressure produced by the NFCA at the field point $\mathbf{r}$ when 1 V is applied to the array input. The right-hand side is a plane wave traveling in the direction $-\hat{e}$. At the reference point located a distance D from the center of the planar NFCA in the direction of the plane wave, i.e., $\mathbf{r} = -D\hat{e}$, the right-hand side becomes $-i\lambda D S_{V,\mathrm{ref}}/A$. Thus the near-field transmitting voltage response $S_{V,\mathrm{NFCA}}$ of the NFCA is given by

$$S_{V,\mathrm{NFCA}} = (-i\lambda D/A) S_{V,\mathrm{ref}}. \tag{11}$$

Since the reference element is a reciprocal transducer, its receiving current sensitivity $M_{I,\mathrm{ref}}$ is related to its transmitting voltage response by use of the complex spherical wave reciprocity parameter J (Ref. 8):

$$M_{I,\mathrm{ref}} = J S_{V,\mathrm{ref}} \tag{12}$$

or

$$M_{I,\mathrm{ref}} = (4\pi D/i\omega\rho)\exp(ikD) S_{V,\mathrm{ref}}, \tag{13}$$

where ρ is the density of water. The receiving voltage sensitivity $M_{V,\mathrm{ref}}$ of the reference element is related to its receiving current sensitivity through the element input electrical impedance $Z_{e,\mathrm{ref}}$ by the expression

$$M_{V,\mathrm{ref}} = Z_{e,\mathrm{ref}} M_{I,\mathrm{ref}}. \tag{14}$$

The input electrical impedance of the reference element at the NFCA operational frequencies is essentially that of a capacitance, i.e.,

$$Z_{e,\mathrm{ref}} = 1/i\omega C_{\mathrm{ref}}, \tag{15}$$

where C_{ref} is the capacitance of the unshaded reference element. Combining Eqs. (11) and (13)–(15) results in

$$S_{V,\mathrm{NFCA}} = (i\omega\rho c/2A)\exp(-ikD)(MC)_{\mathrm{ref}}. \tag{16}$$

Since $M_{V,\mathrm{ref}}$ is essentially independent of frequency for the operational range of the NFCA, the magnitude of the near-field transmitting voltage response of the NFCA increases linearly with frequency.

The near-field transmitting current response $S_{I,\mathrm{NFCA}}$ of the NFCA is related to the near-field transmitting voltage response through the NFCA input electrical impedance $Z_{e,\mathrm{NFCA}}$ by the expression

$$S_{I,\mathrm{NFCA}} = Z_{e,\mathrm{NFCA}} S_{V,\mathrm{NFCA}}. \tag{17}$$

Combining Eqs. (15) and (16) results in

$$S_{I,\mathrm{NFCA}} = (i\omega\rho c/2A) Z_{e,\mathrm{NFCA}} \exp(-ikD)(MC)_{\mathrm{ref}}. \tag{18}$$

Since the NFCA input electrical impedance is given by

$$Z_{e,\mathrm{NFCA}} = 1/i\omega C_{\mathrm{NFCA}} \tag{19}$$

for frequencies well below resonance, where C_{NFCA} is the capacitance of the NFCA, one obtains

$$S_{I,\mathrm{NFCA}} = (\rho c/2AC_{\mathrm{NFCA}})\exp(-ikD)(MC)_{\mathrm{ref}}. \tag{20}$$

This expression shows that the magnitude of the near-field transmitting current response of the NFCA is essentially independent of frequency.

Here, M_{ref} can be replaced in Eq. (20) by its equivalent $JS_{I,\mathrm{ref}}$ to obtain

$$S_{I,\mathrm{NFCA}} = (-i\lambda DC_{\mathrm{ref}})/(AC_{\mathrm{NFCA}}) S_{I,\mathrm{ref}}. \tag{21}$$

III. NEAR-FIELD RECEIVING SENSITIVITY

The near-field receiving voltage sensitivity of the NFCA can be obtained by replacing $S_{I,\mathrm{NFCA}}$ and $S_{I,\mathrm{ref}}$ in Eq. (21) by their equivalents $M_{V,\mathrm{NFCA}}/J$ and $M_{V,\mathrm{ref}}/J$. This gives

$$M_{V,\mathrm{NFCA}} = (-i\lambda DC_{\mathrm{ref}})/(AC_{\mathrm{NFCA}}) M_{V,\mathrm{ref}}. \tag{22}$$

Since $M_{V,\mathrm{ref}}$ is assumed to be constant over the frequency range of operation Ω of the NFCA, then the corresponding near-field receiving voltage sensitivity of the NFCA is inversely proportional to frequency.

The near-field receiving current sensitivity $M_{I,\mathrm{NFCA}}$ of the NFCA is related to the near-field receiving voltage sensitivity through the NFCA electrical impedance $Z_{e,\mathrm{NFCA}}$ by the expression

$$M_{I,\mathrm{NFCA}} = M_{V,\mathrm{NFCA}}/Z_{e,\mathrm{NFCA}}. \tag{23}$$

Use of Eqs. (14), (15), (19), and (23) allows Eq. (22) to be modified to obtain the following expression for the near-field receiving current sensitivity of the NFCA:

$$M_{I,\mathrm{NFCA}} = (-i\lambda D/A) M_{I,\mathrm{ref}}. \tag{24}$$

IV. MODIFIED EXPRESSIONS FOR COMPLEX EXTERNAL LINE SHADING

The expressions given above are based on the assumption that the required shading is real (amplitude only) and is implemented passively with the use of shading capacitors. Let us now consider a projecting planar NFCA where each of the L lines is driven with individual phase-locked amplifiers, as for example, when the coefficients β_l, and thus β'_l, are complex quantities, containing both amplitude and phase shading. If the complex gain g_l of each amplifier is adjusted so that

$$g_l = |(MC)_{\mathrm{ref}}/(MC)_{\mathrm{ref},l}|\beta'_l, \tag{25}$$

then the expressions for the near-field transmitting voltage response given in Eqs. (11) and (16) still apply. Again the reference quantity $(MC)_{\mathrm{ref}}$, also designated $(MC)_{\mathrm{max}}$, is the

largest of the individual line values $(MC)_{ref}$, $l = 1, 2, \ldots, L$. The appropriate input voltage to the NFCA is now the common input voltage for all of the amplifiers. A complex set of external line shading coefficients β_l' usually includes values with a magnitude significantly greater than unity, sometimes as large as 1.5 or 2.0.

For a receiving NFCA when complex values are used for β_l', one can individually measure the voltage output V_l for each line and sum the resulting L values via a computer with relative line shading coefficients h_l given by

$$h_l = \frac{C_l}{(C_l)_{max}} \frac{(MC)_{ref}}{(MC)_l} \beta_l' \qquad (26)$$

Here, C_l is the capacitance of the lth line and $(C_l)_{max}$ is the maximum line capacitance value. The apparent near-field receiving voltage sensitivity for the NFCA in this configuration is then given by

$$M_{\rm NFCA} = [\,i\lambda DC_l/A(C_l)_{max}\,]M_{ref}, \qquad (27)$$

where the appropriate NFCA output voltage v is equal to the sum

$$v = \sum_l h_l V_l . \qquad (28)$$

For the usual case where the lines in the NFCA are identical, or nearly so, then both g_l and h_l become equal to β_l'.

V. SUMMARY

The Trott near-field calibration array can be used as a projector to produce a nearly uniform plane wave over a large volume near the array, i.e., in the array's near field. As such it can be used to obtain the far-field sensitivity of a hydrophone placed in the volume. It can also be used to provide a plane wave incident on a scattering target located in the near-field volume. As a receiver the NFCA is a plane-wave filter and can be used to determine the far-field pressure radiated by a projector or scattered from a target located in the near-field volume. Previous papers considered the design of the array configuration and computation of the associated element shading coefficients for a prescribed near-field volume and frequency range. In this paper expressions are presented for the near-field transmitting voltage and current responses and near-field receiving voltage and current sensitivities of a planar NFCA. In addition, information is given to aid in the NFCA element selection process, especially with regard to shading of the NFCA.

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